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Real-Time and High-Fidelity Simulation Environment for Autonomous Ground Vehicle Dynamics

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GVSETS

Report Documentation Page

Form Approved
OMB No. 0704-0188

1. REPORT DATE	2. REPORT TYPE	3. DATES COVERED
07 AUG 2013	**Briefing Charts**	**05-07-2013 to 03-08-2013**

4. TITLE AND SUBTITLE	5a. CONTRACT NUMBER
Real-Time and High-Fidelity Simulation Environment for Autonomous Ground Vehicle Dynamics	5b. GRANT NUMBER
	5c. PROGRAM ELEMENT NUMBER
6. AUTHOR(S)	5d. PROJECT NUMBER
Jonathan Cameron; Steven Myint; Calvin Kuo; Abhi Jain; Harvard Grip	5e. TASK NUMBER
	5f. WORK UNIT NUMBER
7. PERFORMING ORGANIZATION NAME(S) AND ADDRESS(ES)	8. PERFORMING ORGANIZATION REPORT NUMBER
Jet Propulsion Laboratory,California Institute of Technology,1200 East California Blvd,Pasadena,CA,91125	**; #24087**
9. SPONSORING/MONITORING AGENCY NAME(S) AND ADDRESS(ES)	10. SPONSOR/MONITOR'S ACRONYM(S)
U.S. Army TARDEC, 6501 East Eleven Mile Rd, Warren, Mi, 48397-5000	**TARDEC**
	11. SPONSOR/MONITOR'S REPORT NUMBER(S)
	#24087

12. DISTRIBUTION/AVAILABILITY STATEMENT
Approved for public release; distribution unlimited

13. SUPPLEMENTARY NOTES
GROUND VEHICLE SYSTEMS ENGINEERING AND TECHNOLOGY SYMPOSIUM (GVSETS), SET FOR AUG. 21-22, 2013

14. ABSTRACT
briefing charts

15. SUBJECT TERMS

16. SECURITY CLASSIFICATION OF:			17. LIMITATION OF ABSTRACT	18. NUMBER OF PAGES	19a. NAME OF RESPONSIBLE PERSON
a. REPORT	b. ABSTRACT	c. THIS PAGE			
unclassified	**unclassified**	**unclassified**	**Public Release**	**23**	

Ground Vehicle Research Simulation Tradeoffs

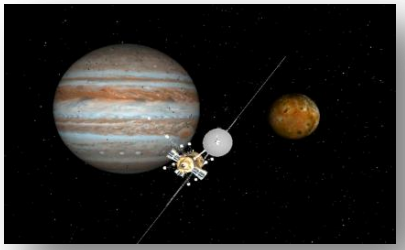
- Fast but low physical fidelity
  - Block that slides on the ground
- High physical fidelity but slow
  - Highly detailed model

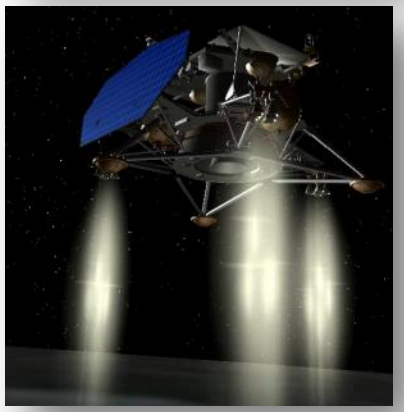
Goal of Research

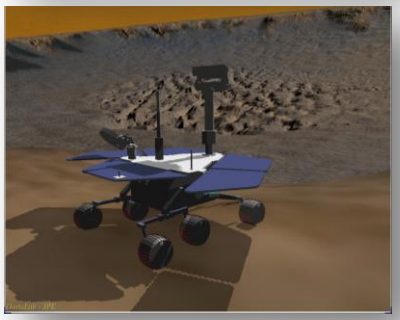
- Construct a ground vehicle simulation that is fast with good physical fidelity
  - Real-time
  - Full suspension, wheel-soil interaction, navigation, and control

ROAMS

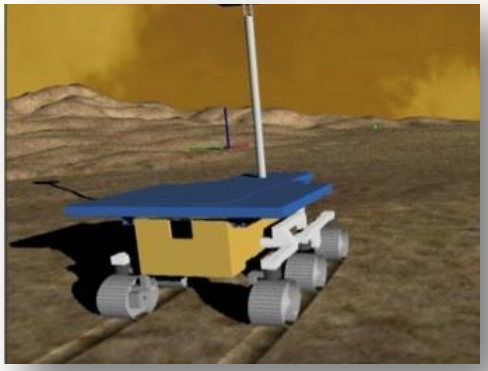
- The JPL DARTS lab team has been involved in vehicle modeling and simulation for over 20 years
- Many key JPL/NASA missions require high-fidelity simulations
  - Spacecraft missions (Cassini, MER, MSL)
  - Planetary rovers (Pathfinder, MER, MSL, research rovers)
- The DARTS lab team created ROAMS for ground vehicle simulations of planetary rovers (http://dartslab.jpl.nasa.gov)

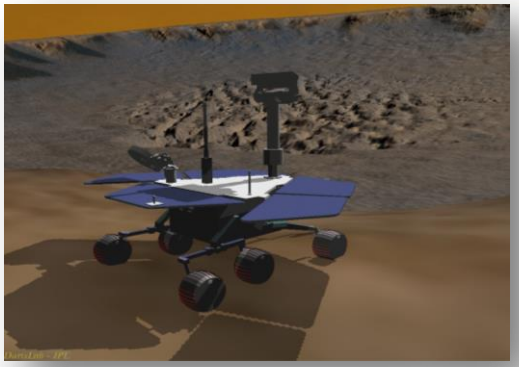


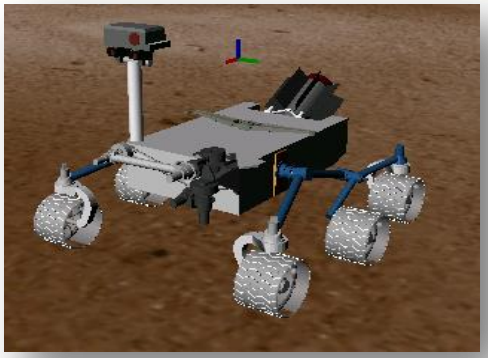


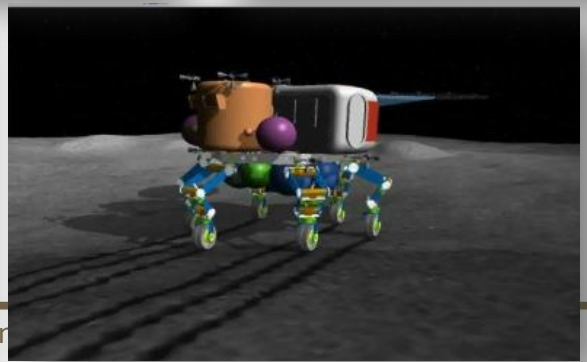


Example ROAMS Vehicles

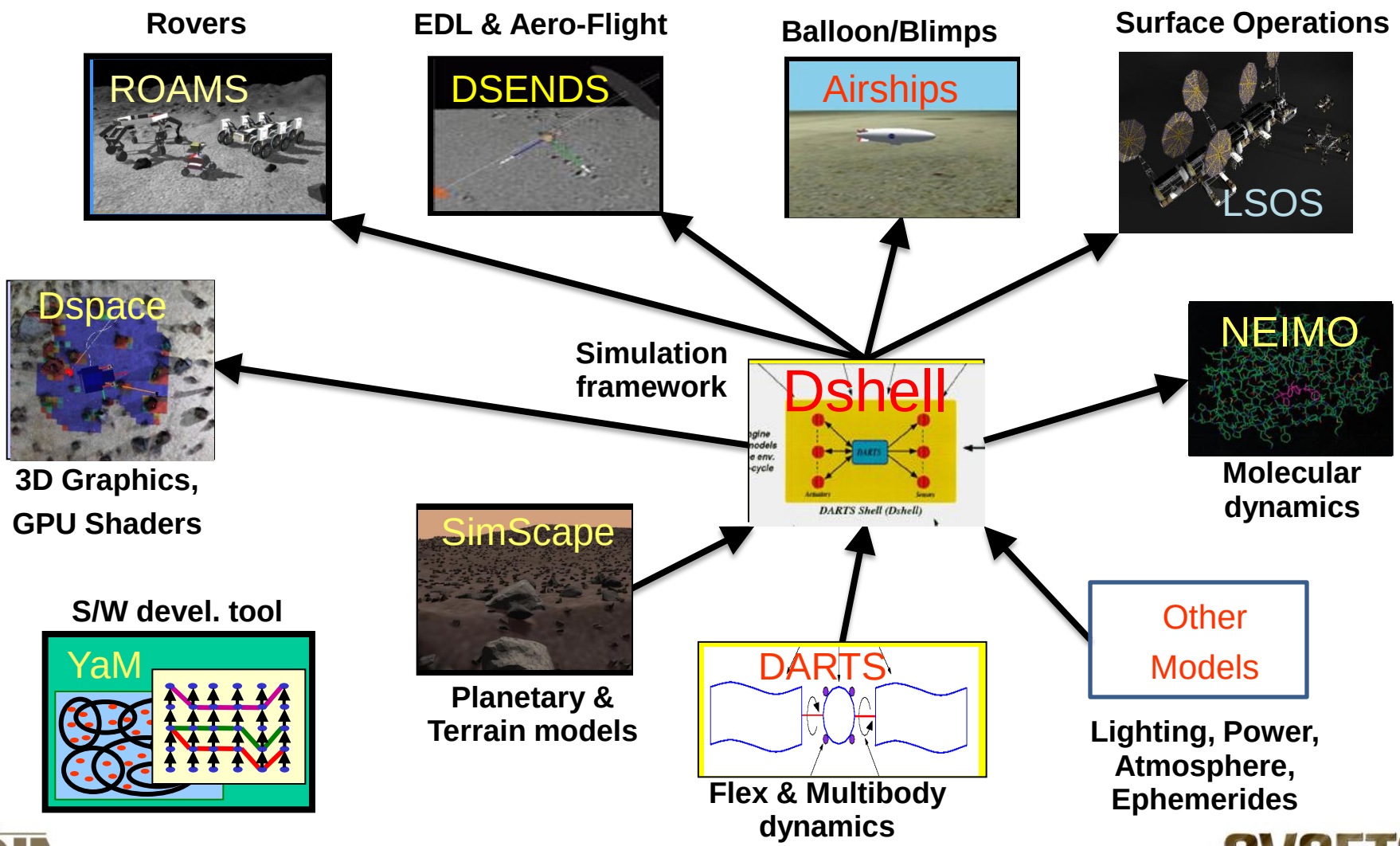








DARTS Lab Physics-Based Tools



ROAMS Simulation Models

Encoders
IMU
Sun sensor
Sensor devices

Rover Vehicle & Arm
Dynamics and Kinematics

battery
solar panels
Power models

Visualization
Dspace

Goal Commands
Way-Point Generation

Motor Control
Controllers

Cameras
Vision/Nav. Sensors

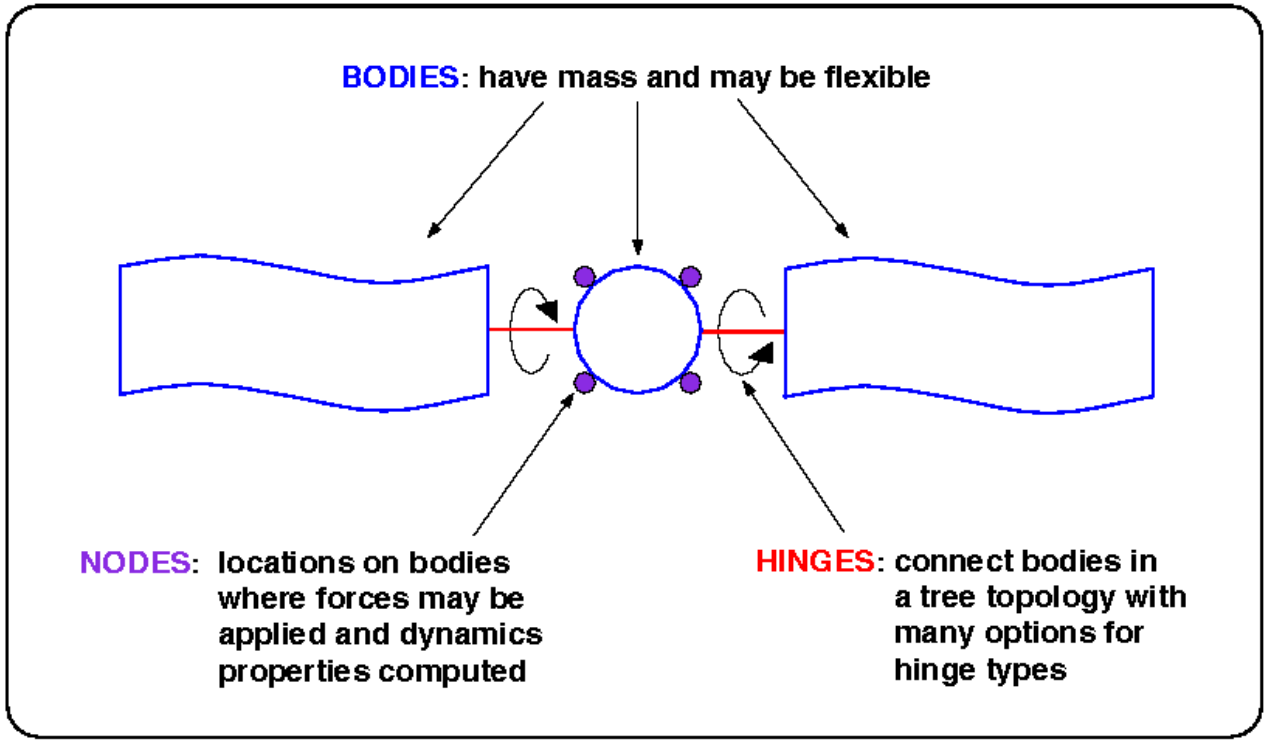
Navigation
Locomotion & Haz. Avoidance
Stereo Vision

DEM, Mesh
Terrain data

Science
Instruments

Compliance model
Contact model

DARTS
Rigid/Flexible Real-Time Multibody Dynamics Engine



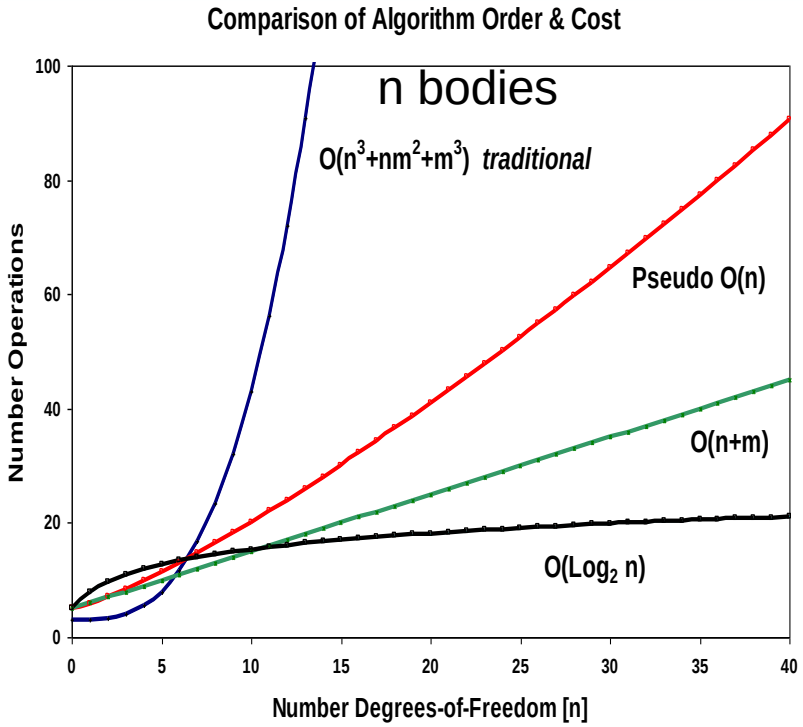
* **DARTS** solves equations of motion for flexible multi-body system based on the dynamics properties of the bodies in the system and the forces applied to those bodies. Based on *Spatial Operator Algebra* state-of-the-art algorithms

Recipient of the NASA Software of the Year Award.

Abhinandan Jain, "Robot and Multibody Dynamics: Analysis and Algorithms", Springer, 2010.

DARTS : Rigid/Flexible Multibody Dynamics Engine

- Kinematics and Dynamics of rigid/flex multibody systems
- Uses minimal DOF, **internal coordinate** formulation – eliminates constraints, is an **ODE** approach, and has superior numerical properties;
- Implements highly efficient **O(N)** recursive multibody dynamics algorithm in contrast with the more commonly used $O(N^3)$ algorithm
- Based on **Spatial Operator Algebra** mathematical framework for multibody dynamics.
- General purpose with model data driven interface
- Models **multi-flexible** body systems and captures nonlinear rigid/flex nonlinear coupling



The more common and traditional approach uses a DAE formulation

Pros

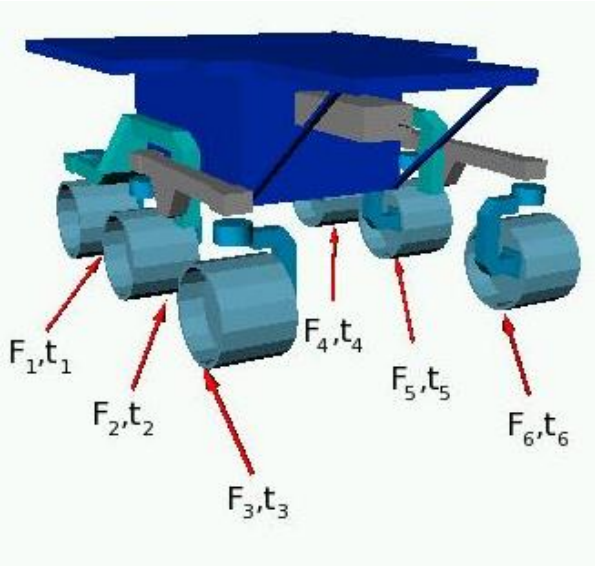
- Full descriptor formulation
- Ability to handle any arbitrary constraint
- Diagonal mass matrix
- Conceptually easy to understand

Cons

- Computationally expensive
- Inexact constraint satisfaction
- Numerical issues of DAEs - stability and non-physical oscillations, convergence, singularity

Wheel/Soil Terramechanics

- **Contact forces and torques on a six-wheel rover are statically indeterminate**
  - 6x(6 wheels) = 36 unknowns
  - 6 equations (+3 for rocker/bogey)
- **Wheel/soil interaction model**
  - Lumped model for wheel/soil interaction (Bekker/Terazaghi)
  - Use Hunt/Crossley spring/damper models for normal forces at each whee
  - Traction model to detect when in slippage regime – uses 2D tangent plane, 2 DOF spring/damper compliance model for contact point.
  - Tune model parameters based on empirical data



G. Sohl and A Jain, "Wheel-Terrain Contact Modeling in the Roams Planetary Rover Simulation," Fifth ASME International Conference on Multibody Systems, Nonlinear Dynamics and Control, Long Beach, CA, September 2005.

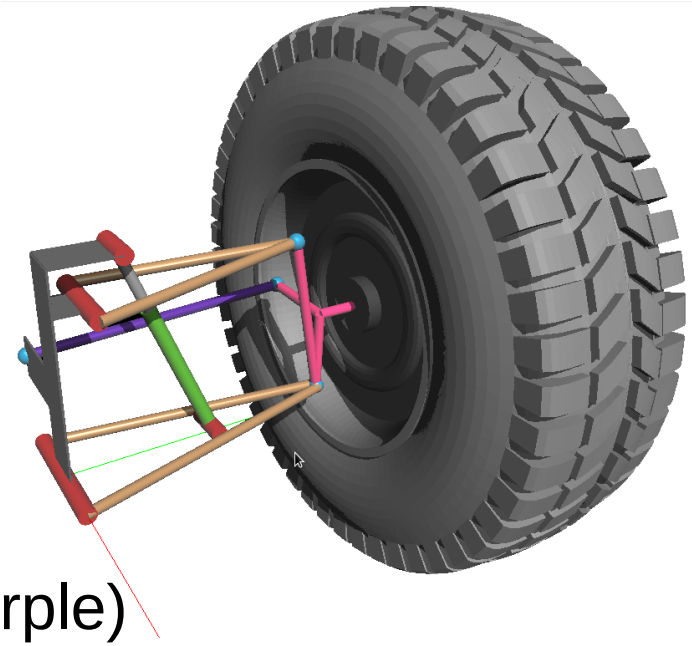
HMMWV Simulation Model

We chose to simulate the HMMWV vehicle

- Representative military vehicle
- Complex suspension
- U.S. Army interest as sensor platform
- Vehicle parameters from existing ADAMS model

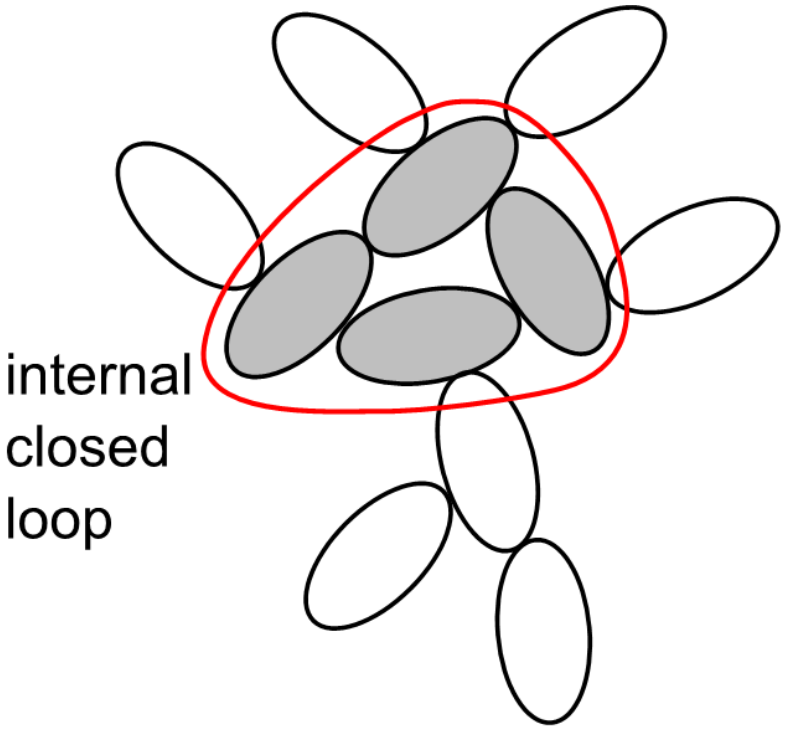
HMMWV Quarter-Car Model

- Complex suspension model for each wheel
  - 5+ bodies (including chassis) in closed chain
  - revolute and ball joints
- Double “A-arm” suspension on each wheel
  - 2 A-arms (tan)
  - Spring-damper (green)
  - Wheel mount (pink)
  - Rider arm / steering linkages (purple)
- Not modeled: revolute joint bushings, drive train

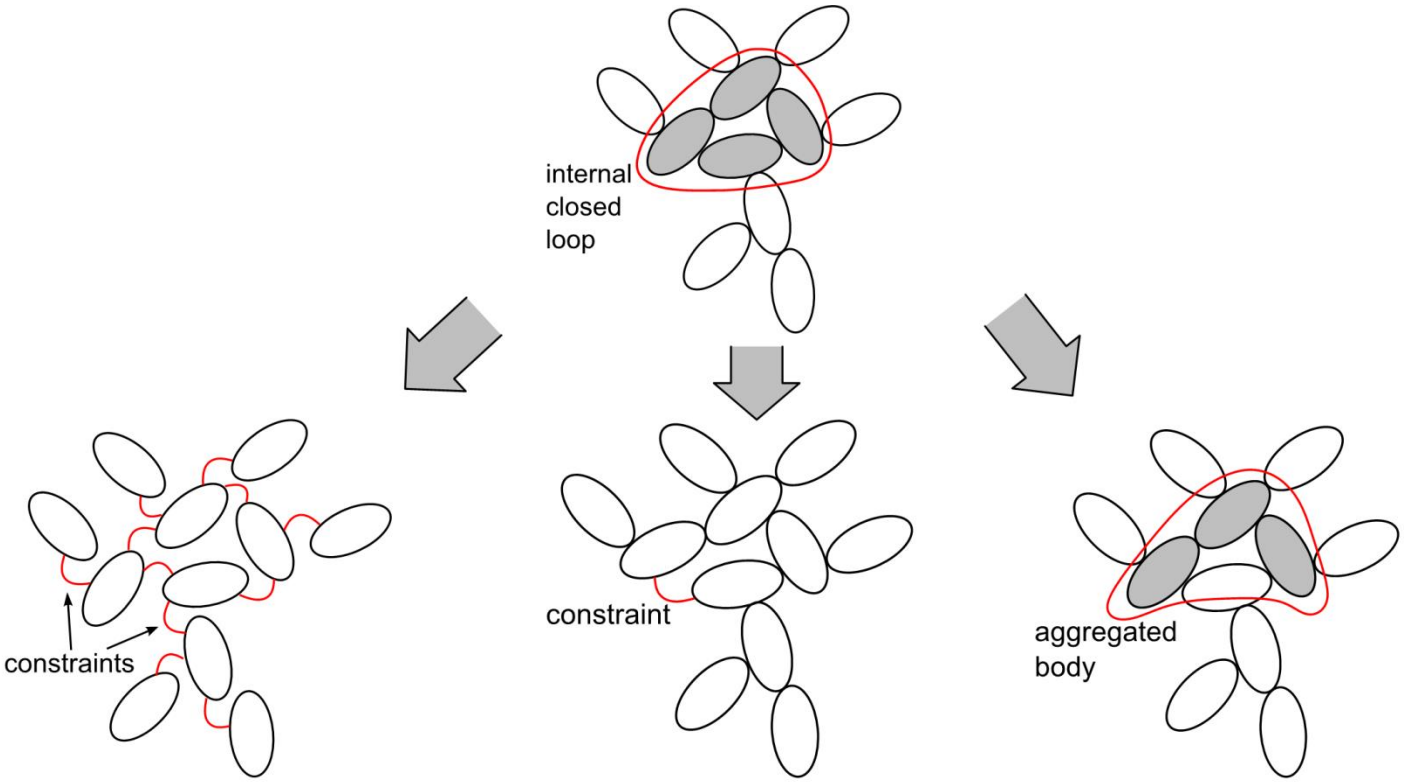


Modeling Closed Chains

- Modeling multi-body systems with “closed chains” is inefficient
- Tree topologies can be modeled using efficient recursive techniques to model body forces and motions



Modeling Closed Chains



Fully Augmented (FA) model (DAE)

Non-minimal coords + constraints

Simple setup

Tree Augmented (TA) model (DAE)

Minimal tree coords + constraints

Better for large loops

Constraint Embedding (CE) model (ODE)

Minimal coords

Optimal for small loops

Comparison of multi-body modeling efficiency for HMMWV model

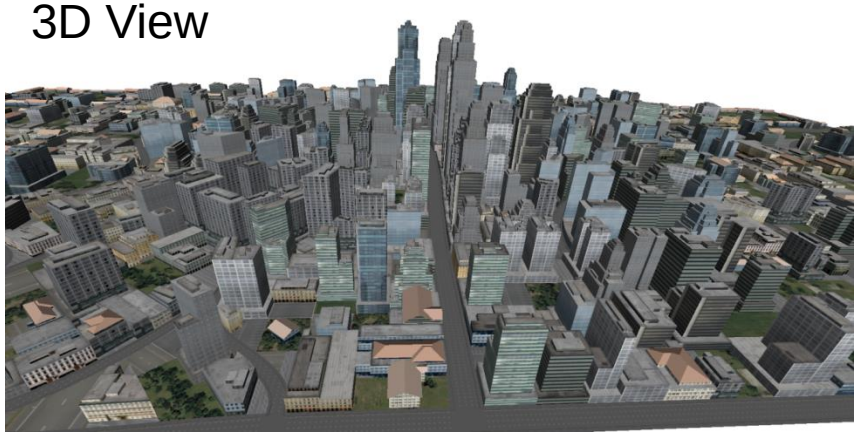
Method	No. of coordinates	No. of constraints	Augmented size	Sim time ratio
CE	15	0	15	1
TA	45	30	75	4.1
FA	216	201	417	120.0

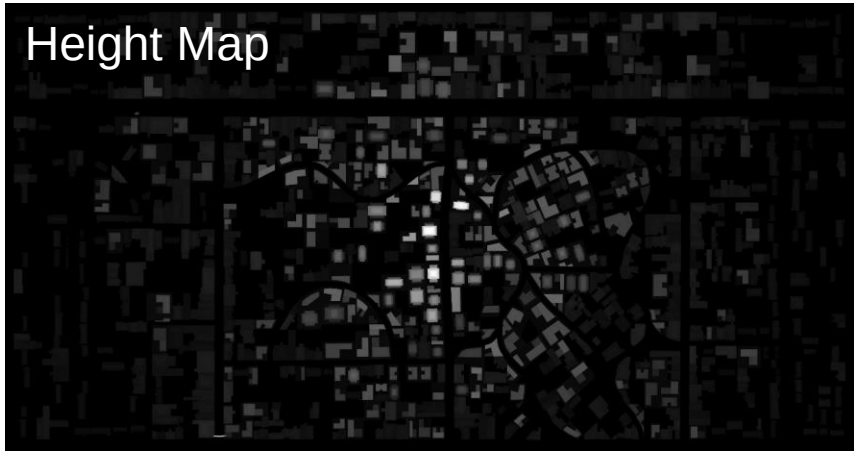
Urban Simulation Environment

Urban Simulation Environment (1km x 2km)

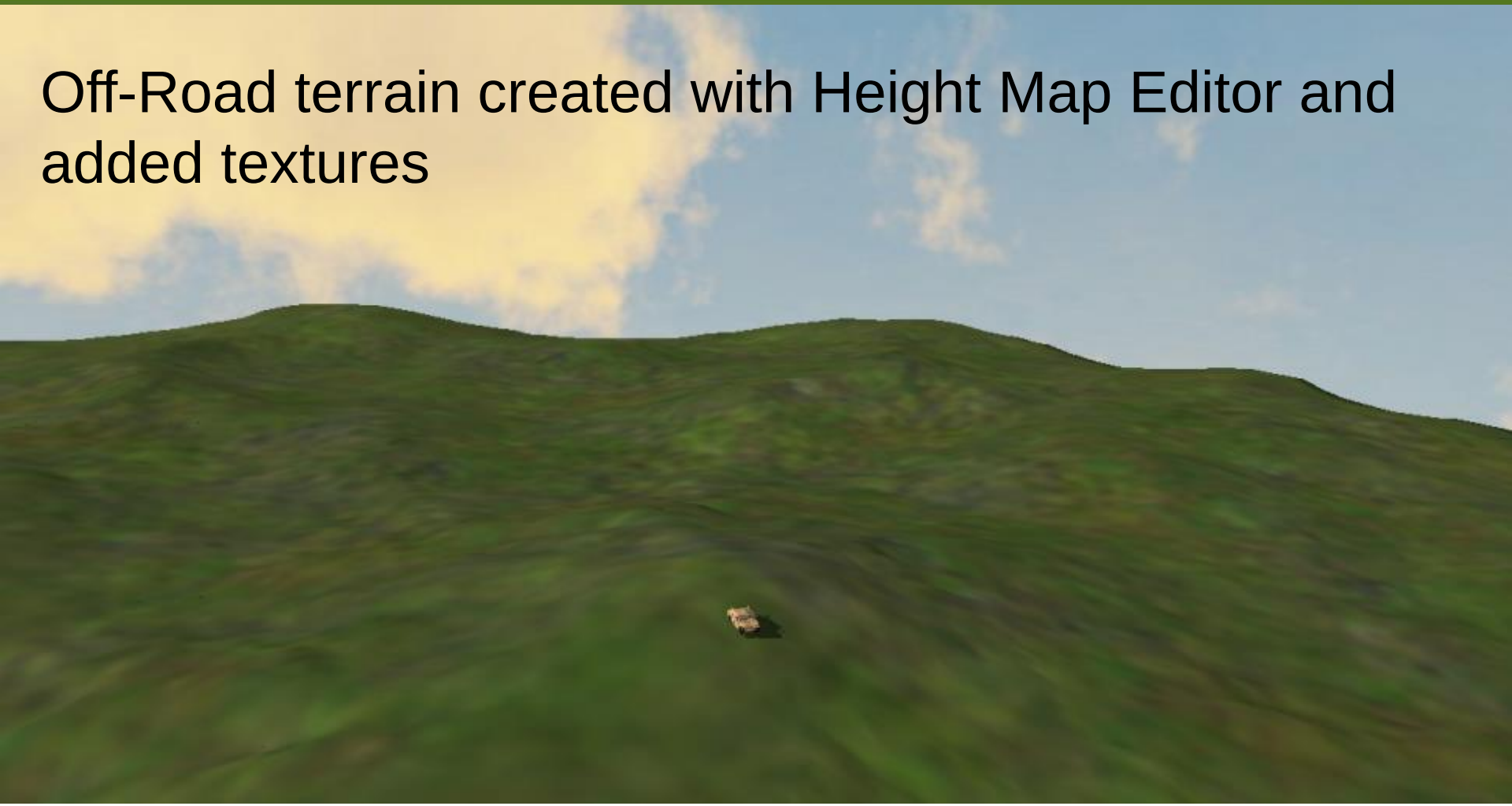
- Created using CityEngine
  - Combines high-rise section (middle) and “sub-urban” (outer)
  - Straight and curved roads
- Extracted surface height map for wheel-soil models

3D View



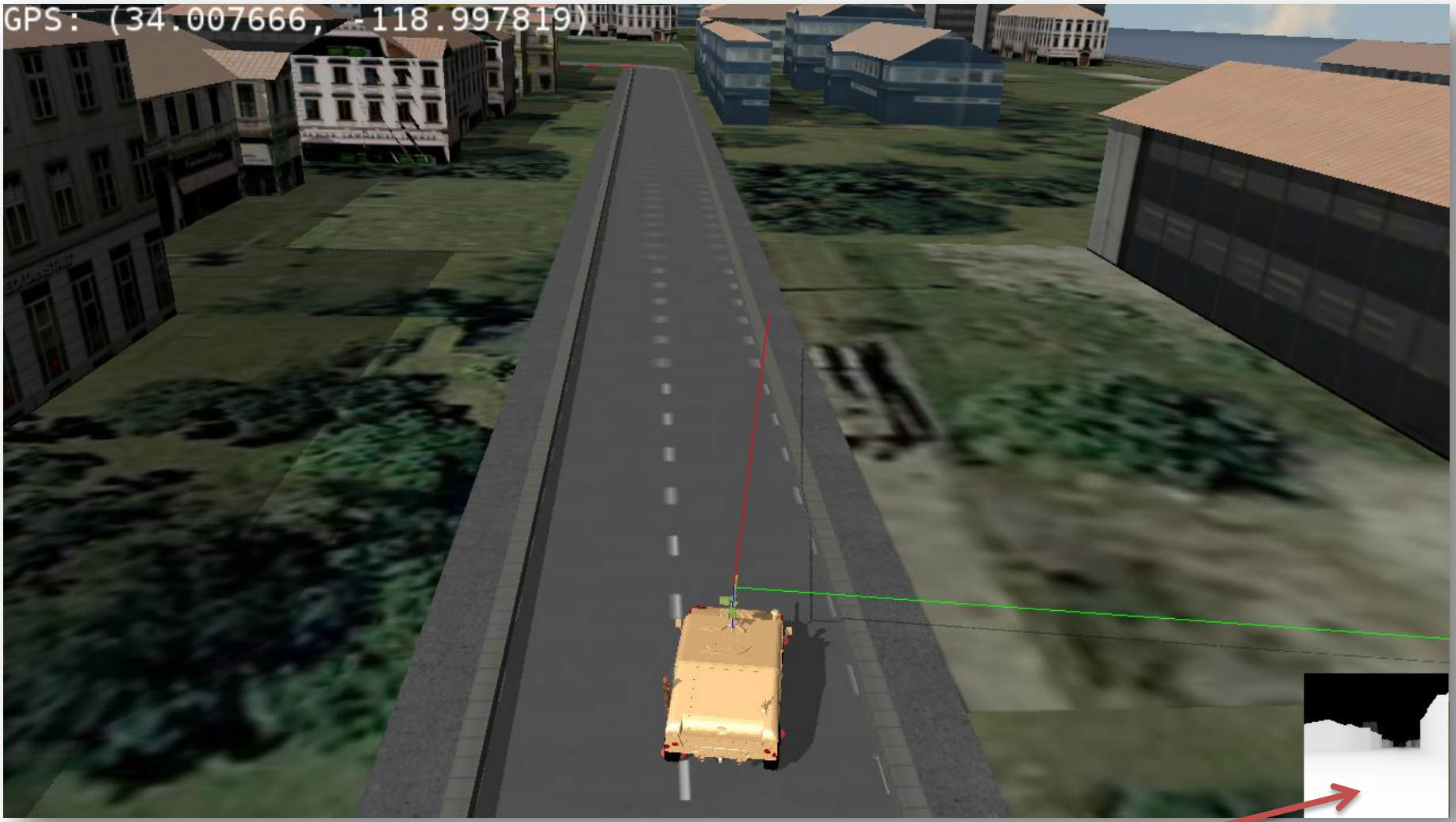


Off-Road terrain created with Height Map Editor and added textures



HMMWV Simulation in Urban Environment

MSTV
MODELING AND SIMULATION, TESTING AND VALIDATION

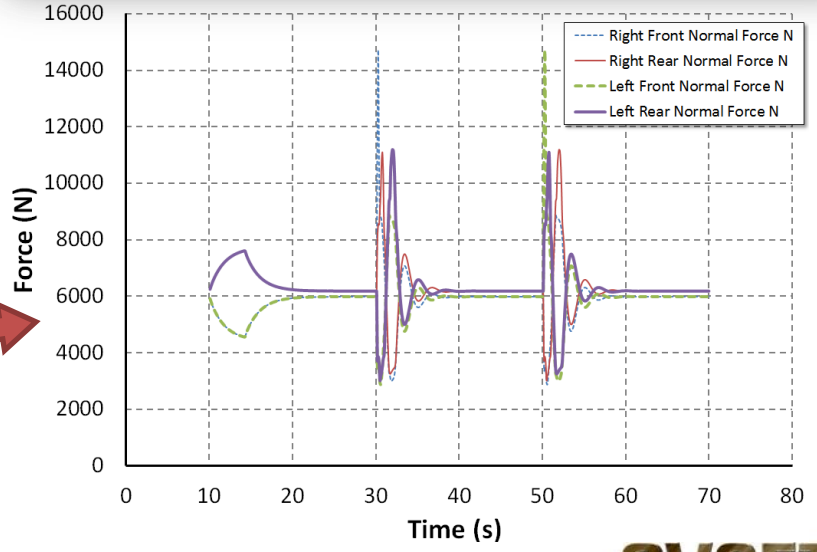


HMMWV Simulation in Urban Environment (autonomous)

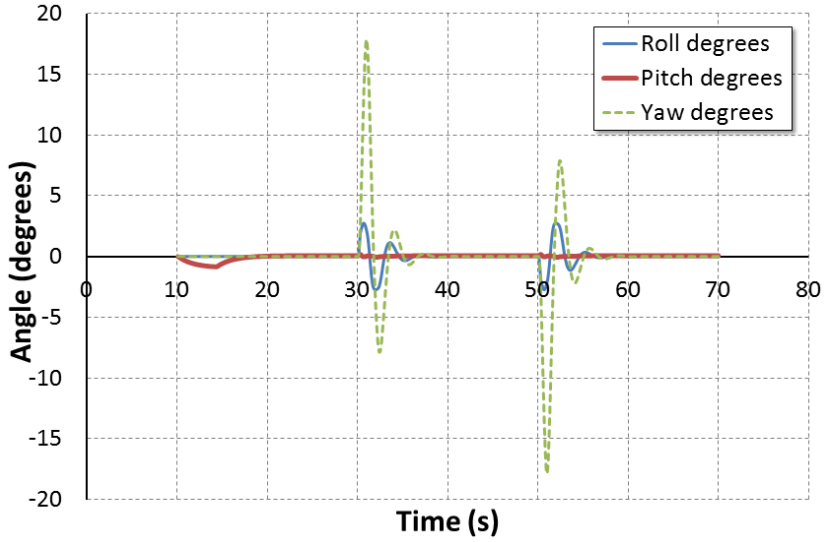
Lane Change Maneuver

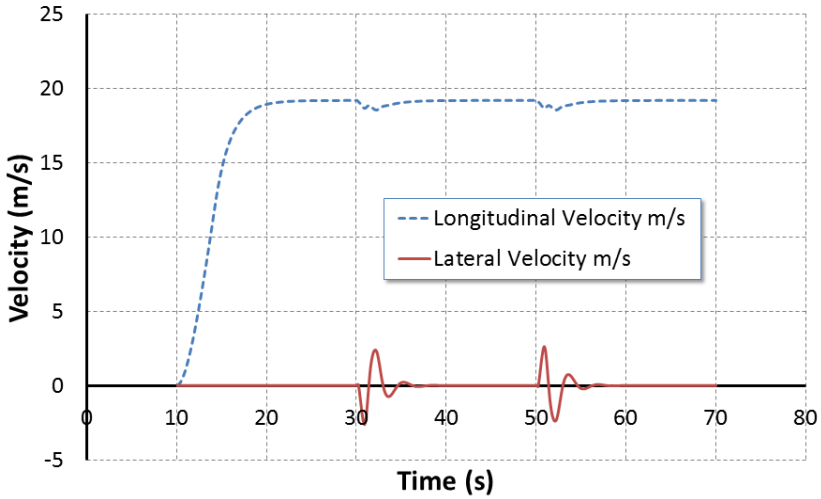
- Speed up to 20 m/s (72 kph)
- Change lanes at 30s
- Maintain lane for 20s
- Change back to original lane

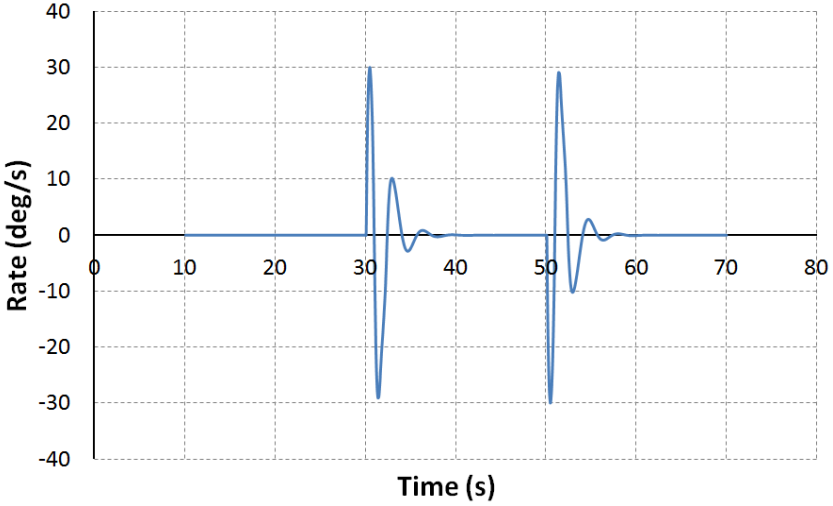
Normal forces acting vertically on wheels by the soil

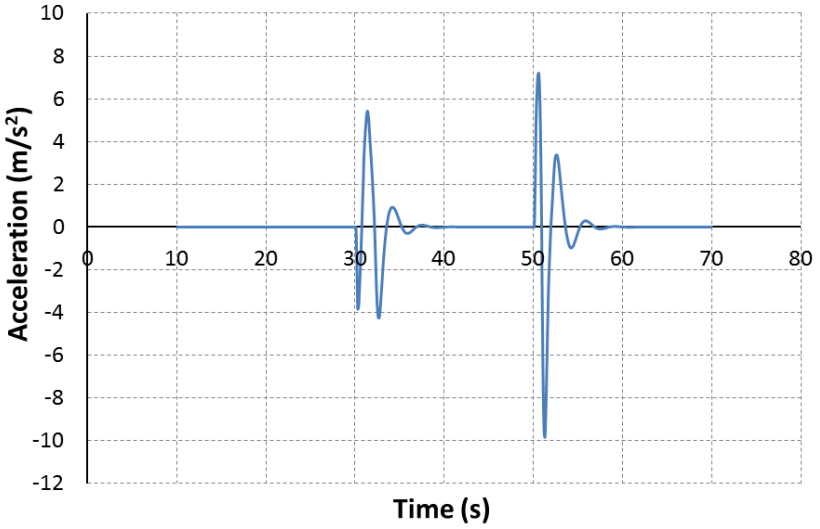


Lane Change Maneuver Plots









Off-road simulation

Simulated control of HMMWV on off-road using teleoperation (joystick for driver steering and gas/brake)

Conclusions

- Demonstrated high-fidelity HMMWV model
  - Full multi-body dynamics model of front and rear suspension, and steering
    - Significant advantages using constraint-embedding approach
  - Sensor models (LIDAR, GPS, cameras)
  - Navigation and control
  - Operates at ½ real-time (without optimization)
- Useful for HMMWV modeling simulations
  - Sensor simulations, vehicle design, etc
  - Being deployed at ERDC with VANE
- Techniques could be applied to other types of military vehicles

Potential Future Work

- Potential areas to improve suspension model
  - Anti-sway bar
  - Bushings
  - Drive train
  - Steering column dynamics
- Validation against real vehicle data